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APD photodetectors in the Geiger photon counter mode

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Abstract

The best detector in Cherenkov experiments still remains the PM tube, thanks to its characteristics of sensitivity and speed. But its disadvantages are its low quantum efficiency and its cost. We are currently working on solid-state silicon detectors, used in the Geiger photon counter mode.

We have conducted a series of tests using standard APD, but with an electronic circuitry to raise the polarisation towards the Geiger mode. The photodiode is polarised over its own breakdown bias, one single photon passing through it may start an electron avalanche resulting in about 10^6 electrons collected. After that, the diode should recover as soon as possible to be available for the next photon.

This process is under modelization: electrical diagrams (PSPICE), differential equations (VHDL-AMS) and components physics equations (SABER) are needed to reproduce closely the physical processes and to allow optimisation and improvement of the electronics both for triggering and for the readout of the detectors.

Keywords: SiPM; APD Geiger; Photon counter mode; Modelization

1. Introduction

The avalanche photodiode meet an increasing success in many applications where only the photomultiplier tube was previously used. We present here a first evaluation in view of possible applications in the field of astrophysics.

Work has been conducted in this field by various groups [1–3] and some production is already available. We do not have yet such components at our disposal, but we have designed a process to go soon in production. Simulations have been conducted, as well on the design of the photodiode itself, as on the driving circuitry and readout electronics. Live tests have been conducted using standard commercially available APD, biased to reach Geiger mode regime.

These electrical results, as well as the simulation for a real Geiger mode APD (SPAD) will be given. The objective here is to be able to produce a model of basics components, and to be able to insert them in a driving circuit. We will first consider a physical model of the Geiger mode avalanche, with an inductive effect due to the onset of the multiplication effect (exponential avalanche) in the space of charge, followed by an effect of capacitive discharge connected to the removal of carriers accumulated in the field of space. We propose to move from the physical model to the electrical model, and we show that it is well suited for the electronics simulations (SPICE). We will conclude with indications towards points, which can be improved.

2. Geiger mode

The photodiode works in a transient mode as shown in Figs. 1a and b. The photodiode is carried at a functioning point V_G larger than the breakdown voltage V_{av}. This transition is fast enough so that no breakdown multiplication spontaneously takes place (thermal generation of

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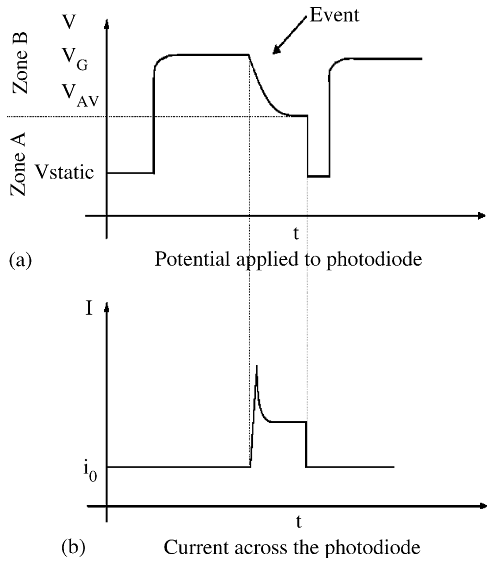

Fig. 1. (a) Potential applied to photodiode and (b) current across the photodiode.

electron hole pairs). If a photon is detected, it will trigger an avalanche mechanism with a multiplication rate N very high, up to 10^8–10^9 electrons per photon, enough to detect directly the photon.

Of course, it is necessary to rearm the diode to be able to restart a new measurement. This is done by lowering the functioning point below the avalanche voltage to evacuate all free carriers. This time of rearmament must be short, because the detector is inoperative during this period. It is obvious that, when the diode polarisation increases, the gain increases as well and hence the photon counting becomes easier (the pulse amplitude will be bigger). But more thermal avalanche can be present. The main limitation of the system is actually connected to carriers which are generated thermally and which define on the other hand the reverse current noise. This limitation implies that the diode can fire spontaneously without any incident photon. This risk will be higher if the rate of thermal generation is high. All of the technological difficulty lies in the resolution of this problem.

3. Modelization

3.1. Physics modelization

The effect of multiplication by avalanche in semiconductors was observed in p–n junctions since the early technological realisations in the 1950s and interpreted as the result of the creation of electron–hole pairs by ionisation. The carrier, electron or hole, accelerated by the very high electrical field in the space charge zone has a certain probability to reach energy such as, by interaction with the crystal net, it creates an electron–hole pair. The detailed modelization of this mechanism, in a p–n junction, where the accelerating electrical field is a function of the position, and where the electrons and the holes have different behaviours, is very difficult. For the sake of comprehension and design, one uses most often simplified models, which consider as equivalent the behaviour of the electrons and the holes, and consider the junctions as defining an electrical field constant in the width of the space charge. The usual formalism is to introduce α, the probability that an electron or a hole creates a new pair in the unit displacement.

Consider first (Fig. 2) a carrier moving at speed v in the space charge zone. When at position x, it induces a charge on the two electrodes, so that their sum is equal to the charge.

Considering, according to Gauss, that the sum of charges of an isolated system is 0, one can write simply

$$\sum^{1} + \sum^{2} = \frac{q(x)}{w} + \frac{q(w-x)}{w} = q.$$

Moving at the speed limit v, the carrier induces a current in the external circuit equal to:

$$i = \frac{\mathrm{d}\sum^{1}}{\mathrm{d}t} = \frac{\mathrm{d}\sum^{2}}{\mathrm{d}t} = \frac{qv}{w}.$$

Considering now that all carriers created in the zone of space charge contribute to the external current as $i = nq(v/w)$.

Starting from this, we can evaluate the transient current implied during a Geiger trigger.

Fig. 3 presents the static operation of a p–n junction. We start from A and raise the applied potential from A to B, B being above the avalanche voltage. The zone of charge space is depleted of all carriers. Nothing happens till a carrier (or the generation of a thermal electron–hole) creates an electron–hole pair. Because of the applied electrical fields, the carriers, electrons and holes, are multiplied in the space charge. This increase of carriers in the field of the space charge can be expressed as

$$\mathrm{d}n = n\alpha \mathrm{d}x = n\alpha v\, \mathrm{d}t$$

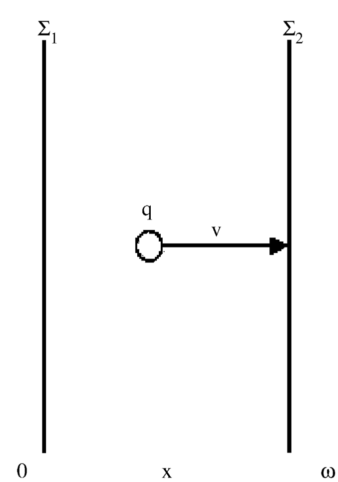

Fig. 2. Electron movement inside the space charge.

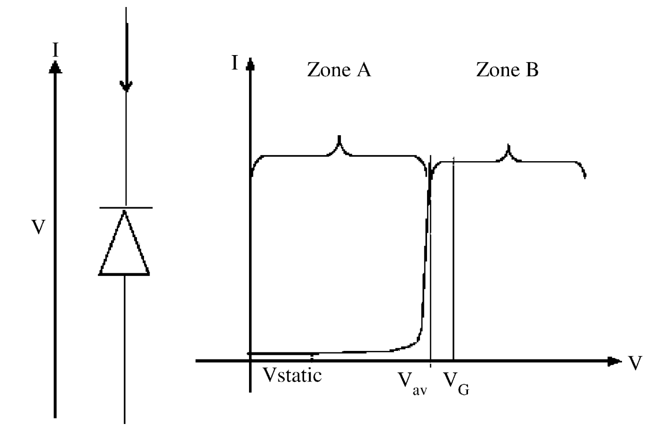

Fig. 3. Static operation of a polarised junction p–n in reverse.

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{v}{w}\alpha w\,\mathrm{d}t$$

$$v = \frac{\mathrm{d}x}{\mathrm{d}t}$$

where n is the number of charge carriers created at time t by a single photon.

α is a function of the electric field E which means a function of a V potential applied to the junction.

With $M = \alpha w$ and $i = nqv/w$, the equation system becomes:

$$\frac{\mathrm{d}i(t)}{\mathrm{d}t} = M(t)\frac{v}{w}i(t)$$

$$M(t) = fct(V(t), t) \quad i(t) = i_0 \exp\left(M(t)\frac{v}{w}t\right)$$

$$V(t) = V_G - \frac{1}{Ci}\int_0^t i(t)\,\mathrm{d}t.$$

One can see:

- The decrease with time of the multiplication factor.
- The shape of the current peak, divided in two phases: the increase of the number of carriers in the space charge, and then the phase of carriers removal.

With the experimental curves presented in Fig. 4, and taking into account the equation system above, one can obtain the current curve (Figs. 5 and 6).

3.2. Electrical modelization

Moving from physical model to the electrical model is difficult because the phenomenon follows non-linear equations. Our physical analysis shows that there is a delay in the setting of the current corresponding to the multiplication effect in the zone of the space charge, then an effect of RC discharge. For the simulation, we propose to model the photodiode, by a capacitance, an inductance, a resistor, a voltage supply and a switch (Fig. 7). When an incident photon arrives (or a thermal electron–hole pair is generated) the switch I is turned off.

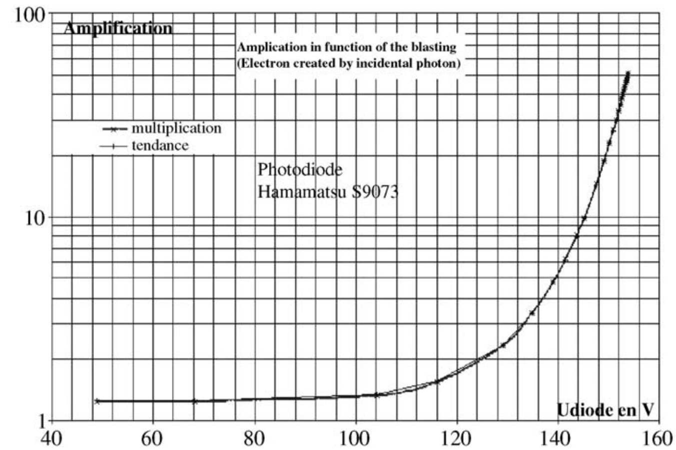

Fig. 4. Amplification factor M as a function of the photodiode bias: experimental curve.

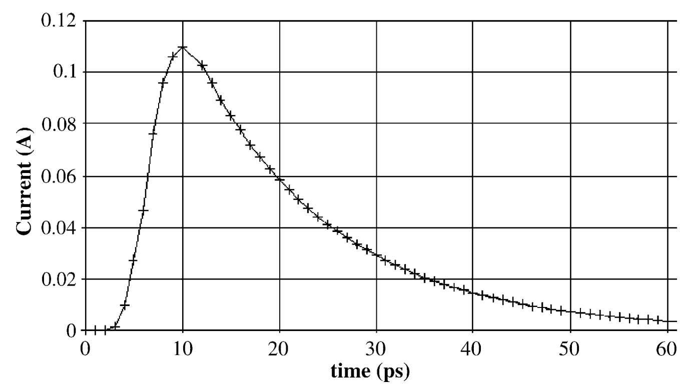

Fig. 5. Current as a function of time.

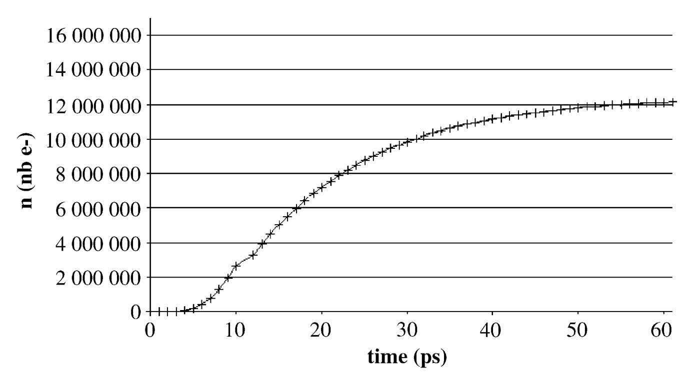

Fig. 6. Number of electron as a function of time.

Immediately, the current increases as

$$\frac{\mathrm{d}i}{\mathrm{d}t} = Mi\frac{v}{w} \quad \text{(Former section).}$$

This current corresponds to the discharge of the junction capacitance and the stray capacitance. The junction bias drops to the breakdown voltage.

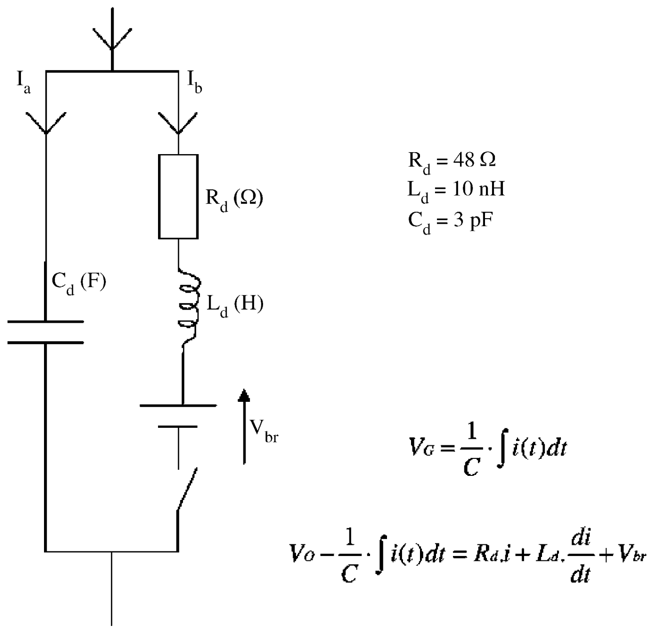

Fig. 7. Electrical model.

This electric modelization (realized by means of VHDL AMS) simulates the behaviour of the photodiode in Geiger mode in the electronic circuits.

Two circuits are implemented: the monitoring and reading circuit and the bias regulating circuit.

4. Conclusion

We have presented in this paper the first results of modelizations and measurements on Avalanche Photo Diodes operated in Geiger mode. This can lead to:

Proposition for a simplified physical model, indicating the increase of the current connected to the multiplication factor. This model is used to get a direct evaluation of the level of multiplication as a function of the applied voltage.

Presentation of an electrical model to describe the operation of the diode in a circuit simulator under VHDL-AMS

The contribution of these two models and their experimental verification will allow the design of a new generation of devices, operating in low voltage, which can be integrated in detector matrices. The basic device comprises two successive diffusions, P^+ on P substrate and N^{++} on P^+. This structure is designed to guard from avalanche effects on the edge of the junctions.

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